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Optimal Relay Coordination of an Adaptive Protection Scheme using Modified PSO Algorithm

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Abstract—Recently, future smart grids are described by a dominantly fluctuating character due to the power consumption change from peak to off-peak loading conditions, the operation of micro-grids in grid-connected or islanded mode and other possible network topologies resulting in an effective change in network impedances and short circuit current level. Therefore, the situation from protection sensitivity, selectivity and speed may become more and more challenging. In this paper, Adaptive protection scheme is proposed to respond to structural variations occurred in interconnected power systems. A designed software based on Modified Particle Swarm Optimization (MPSO) algorithm is suggested to solve the relay coordination problem in modern distribution networks. In this study, the 14 IEEE bus system is tested via three power system scenarios showing the effect of adding and disconnecting of DG units and the occurrence of sudden line outages on the system. The obtained results show that the proposed algorithm has achieved optimum relay settings for each existing network topology.

Index Terms—Adaptive protection scheme, Modified particle swarm optimization, overcurrent relay coordination

I. INTRODUCTION

Nowadays, the addition of distributed generation (DG) in medium and low voltage power networks involves the use of small-scale distributed energy resources (DERs), which can either operate in parallel to or islanded from the utility grid. Such technologies can offer numerous advantages such as higher operating efficiency, improvement of voltage profile and enhancement of network capacity, but on the other hand has a significant impact on the control, protection and reliability of the existing power system. A traditional protection system is designed to operate for radial distribution networks with unidirectional power flow. The interconnection of DG units will consequently transform the radial topology into meshed structure with bidirectional power flow affecting both the magnitude and direction of fault currents in various parts of the system. [1]. Distribution utilities are usually protected using overcurrent relays (OCRs), which are expected to operate at a fixed fault current level. Whenever the magnitude of short circuit current changes, the degree of failure of such relays to respond to new operating conditions may be increased leading to a miscoordination between the protective devices [2].

Therefore, a modernized protection approach is suggested to accommodate with various changes in the behavior of short circuit current levels, introducing the concept of "**Adaptive Protection scheme**" [3]. Adaptive protection is actually an "online procedure in which the relay settings have to be permanently adapted to the current operating status in order to provide a selective operation for all possible network scenarios". Adaptive protection scheme could be implemented via two phases. In phase-1, the optimum setting groups are obtained using a powerful engineering algorithm for all possible network topologies then stored in the relays in an offline mode. In phase-2, a central controller detects the existing scenario based on the circuit breaker status and selects the appropriate setting groups according to the corresponding network topology [4]. In order to guarantee a fast, reliable and secure power system protection, the coordination of OCRs should be performed by adjusting two setting values: the pickup current (I_p) and the Time Dial Setting (TDS). The pickup current can be defined as the minimum current value for which the relay begins to respond. The TDS adjusts the inverse characteristics of overcurrent device, hence controlling its time delay whenever the fault current reaches a value greater than or equal to the pickup current [5,6]. The coordination of OCRs for future smart grids is considered as a relatively challenging task. Therefore, many intelligent optimization algorithms are used to determine optimum relay settings in modern distribution systems. In [7], the current and TDS settings are optimized using Genetic Algorithm GA for peak and off-peak loading conditions. In [8], J. Sadeh et al. has suggested a hybrid method based on GA and linear programming (LP) to solve the relay coordination problem, in which GA is applied to compute the pickup current settings for OCRs, then TDS are solved in each iteration using linear programming technique. In [9], the authors have presented an adaptive protection scheme based on Ant Colony optimization (ACO) technique to calculate OCR settings. A benchmark comparison is carried out between ACO and GA for several case studies showing that ACO has achieved better results than GA. In [10], the optimization of relay settings is performed using differential evolution (DE) algorithm and a new protection approach is investigated which utilizes an adaptive fuzzy technique to select the optimal relay settings. In [11] and [12], a

Modified Particle Swarm Optimization (PSO) algorithm is suggested to calculate optimal relay parameters. The modification includes the initialization of PSO particles and the addition of a repair algorithm to help PSO satisfying the coordination constraints [12].

In this paper, the concept of adaptive protection scheme is explained and the suggested solution techniques are surveyed in section I. Problem formulation and constraints are stated in section II. The difference between the typical PSO and the proposed Modified PSO algorithm is also highlighted and included in section III. The 14 IEEE bus system is tested for different case studies and results are reported in section IV showing the effectiveness of the proposed approach.

II. PROBLEM FORMULATION

The coordination of OCRs is formulated as a Nonlinear Optimization Problem (NLP) since the relay operating time is a nonlinear function of I_p in accordance with IEC 60255 [13], as expressed in equation (1):

$$t_{op} = TDS \frac{A}{(I_F/I_p)^B - 1} \quad (1)$$

Where (t_{op}) is the relay operating time, (TDS) is the relay time dial setting, (I_p) is the pickup current setting, (I_f) is the fault current, (A) is the constant for relay characteristics, and (B) is the constant representing inverse time type.

A. Objective Function

In the relay coordination problem, the main objective function is to minimize the summation of operating times of all relays, where pickup current and TDS are considered as the decision variables. The general form of objective function is expressed as follows:

$$\min \sum_{k=1}^n (t_{op, k})$$

Where, n is the number of relays in the system and ($t_{op, k}$) is the operating time of the relay R_k .

B. Constraints

The objective function defined above is subjected to the following set of constraints.

1. Selectivity Constraint:

The requirement of selectivity states that when a fault occurs, only the primary relay should operate to trip the fault. If the main relay fails to operate, the backup relay should clear the fault after a pre-specified delay time known as coordination time interval (CTI), normally set between 0.2 s and 0.5 s. In order to satisfy such requirement, the following constraint must be added:

$$T_{backup} - T_{main} \leq CTI \quad (3)$$

Where, T_{main} and T_{backup} are the main and backup operation time, respectively. CTI is the coordination time interval between primary and backup relays.

2. Limit Constraints:

There is always a range for each relay setting, from which feasible solutions are encountered. Therefore, other constraints should be considered on the limits of relay parameters, including TDS and I_p settings, that can be expressed in the following equations:

$$TDS_{min} \leq TDS \leq TDS_{max} \quad (4)$$

$$I_{p min} \leq I_p \leq I_{p max} \quad (5)$$

Where TDS_{min} and TDS_{max} , $I_{p min}$ and $I_{p max}$, are the minimum and maximum limits of Time Dial Setting (TDS), and pickup current (I_p) settings, respectively.

III. PROPOSED PSO ALGORITHM

A. Typical PSO Algorithm

PSO developed by J.Kennedy and R.Eberhart in 1995 is a population based optimization algorithm inspired by the ability of a group of swarming animals such as birds or fishes to work as a whole in a given area searching for corn. This seeking behavior is validated through equations in a real valued search space. Particles move through the search space adjusting their position and their velocities according to equations (6) and (7) based on their own experience and to their neighboring particles experience in order to find the optimal solution.

$$v_i^{k+1} = w \cdot v_i^k + c_1 \cdot rand_1 \cdot (P_{best i} - X_i) + c_2 \cdot rand_2 \cdot (G_{best i} - X_i) \quad (6)$$

$$X_i^{k+1} = X_i^k + v_i^{k+1} \quad (7)$$

$$w = \frac{(w_{max} - w_{min})}{iter_{max}} * iter \quad (8)$$

Where:

w	The inertia weight of the particle that can be calculated using equation (8), where w_{max} is 0.9, w_{min} is 0.4.
$iter_{max}$	The maximum number of iterations
iter	The current iteration.
v_i^k	The velocity of particle (i) for iteration (k)
c_1, c_2	Acceleration rates that pull each particle towards P_{best} and G_{best} positions
$rand_1, rand_2$	Random numbers from 0 to 1
P_{best}	Best position achieved by particle (i)
G_{best}	Best position achieved by all particles in the swarm
X_i	Position of particle (i)

B. Modified PSO Algorithm MPSO

In standard form of PSO, the initial positions are randomly generated in the entire swarm. This by consequence will not ensure that all the initial particles are encountered from feasible solution. In the proposed Modified PSO, the initial solutions are optimized based on a linear programming technique known as the "Interior-point Method". This is performed by selecting the pickup current settings randomly between minimum and

A. Power System Scenario 1

The corresponding scenario represents the normal network condition when both generation units G1, G2 are operated in parallel to supply the corresponding loads. G1 is considered as the main grid, while G2 is used as a distributed generation (DG) unit operating in **grid-connected** mode. The determination of optimum relay setting groups can be performed using the following steps:

- Identifying the primary and backup relay pairs for the system.
- Performing a short circuit analysis to calculate the maximum short circuit current located at the Near-End of each relay.
- Calculating the maximum and minimum boundaries for the pickup current setting. The upper and lower limits of current setting are considered as the full load current and the minimum short circuit current passing through the relay, respectively. Therefore, a load flow analysis is carried out to compute the relays full load currents, while the minimum short circuit current is estimated by assuming a phase-phase fault occurring at the far-end of each circuit breaker.
- Input the calculated data entry in (a, b, c) to the suggested MPSO algorithm then calculate the optimized relay settings according to the illustrated flowchart in fig.1.

The pickup current (I_p) and Time Dial settings (TDS) for all the overcurrent relays are optimized using MPSO algorithm based on a swarm size of 50, and the time settings are selected between maximum and minimum bounds of 0.1 and 1.1 s respectively. The obtained results for I_p and TDS are listed and given in Table II.

TABLE II. TDS AND PICKUP CURRENT RELAY SETTINGS FOR POWER SYSTEM SCENARIO 1

Relay No.	TDS	I_p [A]	Relay No.	TDS	I_p [A]
R1	0.1	1965.4	R16	0.1	8.7
R2	0.1134	1805.9	R17	0.1	77.4
R3	0.1001	547.7	R18	0.1	6.3
R4	0.1	493.7	R19	0.1	39.4
R5	0.1	590.0	R20	0.1	24.2
R6	0.1	454.9	R21	0.1	26.6
R7	0.1412	522.8	R22	0.1001	34.9
R8	0.1	292.7	R23	0.1001	44.2
R9	0.162	496.7	R24	0.1001	24.4
R10	0.1	339.0	R25	0.1	26.3
R11	0.1054	312.9	R26	0.1342	17.1
R12	0.1026	318.4	R27	0.1517	4.8
R13	0.1	550.5	R28	0.1	41.3
R14	0.1001	356.6	R29	0.1061	34.2
R15	0.1236	116.4	R30	0.1	27.6

Fig.3 shows the convergence of the fitness function for the power system scenario 1, which illustrates that MPSO reaches the best solution after approximately 100 iterations. It should be noted that the convergence of fitness function shows the response of PSO algorithm after the optimization of initial generation for a population size of 50 particles using Interior-point-method that reaches approximately 7.9 sec total operating time of all relays as best solution for the initial condition, then minimized to 7.2569 sec after 100 iterations of MPSO algorithm. The coordination time intervals between primary and backup relay pairs are also presented in Fig.4. It should be noted that all the coordination intervals points are maintained between 0 and 0.5 sec which means that MPSO has reached the minimum operating time of all relays while satisfying no more than the predefined selectivity constraint for relay coordination problem.

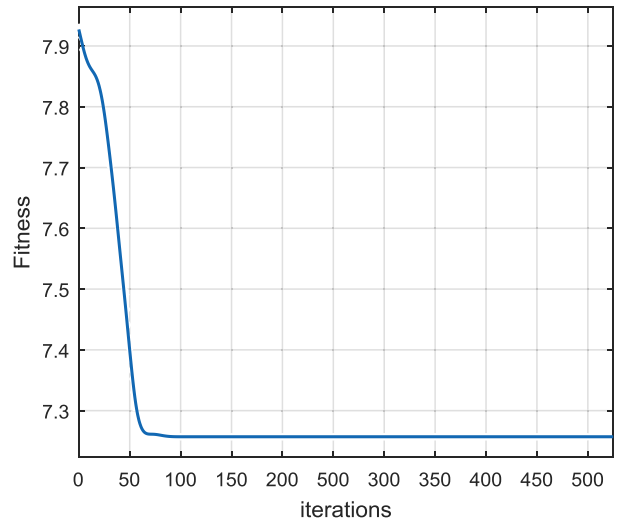


Fig.3: The convergence of proposed fitness function

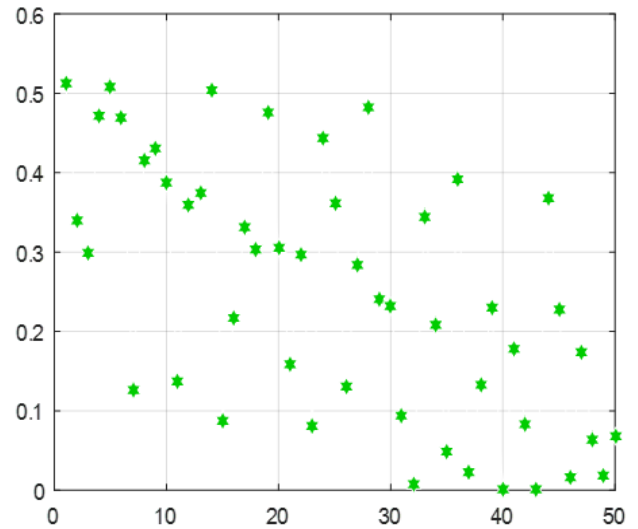


Fig.4: The coordination time interval points for all P/B relay pairs of power system scenario 1 maintained between 0 and 0.5 s.

B. Power System Scenario 2

This scenario describes the operation of distributed generation unit G2 in “OFF-grid” mode. In this topology, G2 is assumed to be disconnected from the system, and only the utility grid is used to supply the whole network. This will result in a significant change in fault current level and hence may affect the selectivity of protective devices. Table III indicate the miscoordination occurred between relay pairs R2 and R6, R2 and R8, R2 and R10, R3 and R2, R22 and R26 respectively, when testing the relay settings calculated in scenario 1 on scenario 2, returning negative coordination intervals. The results of new appropriate relay settings optimized for the second power system scenario are reported in table IV.

TABLE III. MISCOORDINATION SUMMARY OF RELAY PAIRS

Malfunctioning P/ B relays		CTI
R2	R10	-0.75
R2	R8	-0.79
R2	R6	-0.61
R3	R2	-14.1
R22	R26	-0.01

C. Power System Scenario 3

The third scenario describes the system in case that a “single line outage” occurs. Actually, line outages could occur by means of protection issues or maintenance purposes. Two cases of single-lines are selected and tested in order to demonstrate the effectiveness of adaptive protection technique.

- Case 1: describes the system when line 1—2 is disconnected.
- Case 2: describes the system when line 2—5 is disconnected

For each case, the upper and lower limits for relay pairs, and the short circuit currents for near and far end faults are recalculated and new relay settings are optimized to adapt the change in each test case. The computed relay settings for the two case studies are reported and given in Table VI. The convergence of fitness function for power system scenario 3 cases combined with the fitness function of scenario 2 is illustrated in Fig. 5, showing that

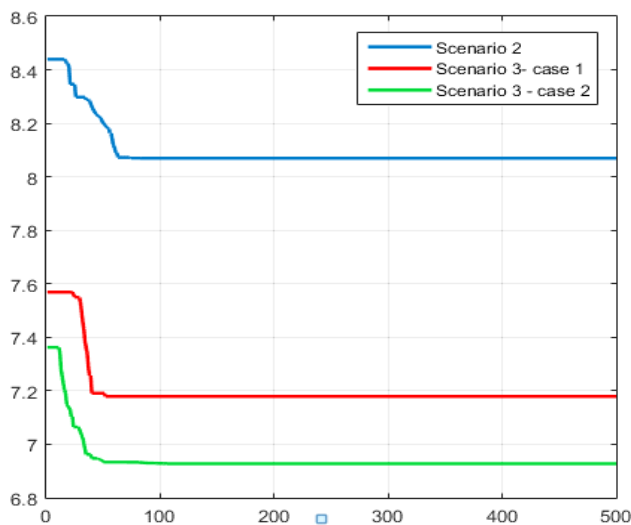


Fig.5: The combined convergence of fitness functions for power system scenarios 2 and 3.

MPSO has achieved minimum operating time for all relays in each scenario.

TABLE IV. TDS AND PICKUP CURRENT SETTINGS SCENARIO 2 AND SCENARIO 3

Relay No.	Power System Scenario 2		Power system scenario 3			
			Case 1		Case 2	
	TDS	Ip [A]	TDS	Ip [A]	TDS	Ip [A]
R1	0.1328	1595	--	--	0.1	1612.44
R2	0.1008	498.14	--	--	0.1	849.139
R3	0.1008	602.11	0.1	803.11	0.1	554.029
R4	0.1005	283.85	0.1	473.50	0.1002	372.817
R5	0.1	462.50	0.1	488.48	0.1	645.203
R6	0.1	466.08	0.1	336.73	0.1	375.508
R7	0.1001	438.42	0.1553	322.69	0.1001	624.696
R8	0.1	279.79	0.1004	313.54	0.1	429.065
R9	0.1220	363.93	0.1002	511.99	--	--
R10	0.1004	326.90	0.1006	418.08	--	--
R11	0.1013	343.99	0.1	479.43	0.1001	518.908
R12	0.1008	289.37	0.1001	491.89	0.1001	480.105
R13	0.1006	515.55	0.1	1155.68	0.1	299.238
R14	0.1006	648.58	0.1002	874.09	0.1	408.657
R15	0.15	64.98	0.1	130.89	0.1	73.3514
R16	0.1005	28.23	0.1005	18.85	0.1	16.967
R17	0.1	37.11	0.1	37.39	0.1001	14.44
R18	0.1002	5.98	0.1	6.346	0.1	6.037
R19	0.1413	121.00	0.1007	68.06	0.1	117.76
R20	0.1009	21.96	0.1	24.59	0.1001	20.944
R21	0.1018	81.02	0.1	93.43	0.1001	69.398
R22	0.1002	30.57	0.1024	18.07	0.1	19.19
R23	0.1008	32.55	0.1002	85.80	0.1005	76.27
R24	0.1	33.76	0.1	17.45	0.1	34.74
R25	0.1	29.48	0.1	29.56	0.1	34.30
R26	0.106	27.59	0.1014	25.69	0.2201	2.5056
R27	0.1	35.66	0.1010	12.25	0.1536	2.915
R28	0.1041	5.212	0.1002	25.50	0.1	56.07
R29	0.1998	9.311	0.1003	48.10	0.1006	46.39
R30	0.1	12.94	0.1	27.19	0.1604	5.96

V. CONCLUSION

In this paper, the MPSO algorithm was proposed to solve the relay coordination problem. The modification added to the typical PSO technique helped to hold all particles in feasible solution. The 14 IEEE bus network has been tested for different power system topologies to validate the concept of adaptive protection scheme. The selected case studies have introduced the effect of DGs penetration and disconnection as well as the line outage occurrence on the distribution networks. The obtained results have demonstrated the effectiveness of the suggested approach in achieving optimum relay setting groups according to each network topology minimizing the total operation time while satisfying the selectivity constraints among all protective devices.

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